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Green Synthesis and Characterization of ZnO Nanoparticles Using *Azadirachta indica* Leaf Extract: A Comprehensive Review

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Abstract:

The growing demand for environmentally sustainable nanomaterials has accelerated the development of green synthesis approaches for metal oxide nanoparticles. This review focuses on the biosynthesis and characterization of zinc oxide (ZnO) nanoparticles using aqueous leaf extract of *Azadirachta indica* (Neem). Neem leaves are rich in bioactive phytochemicals such as flavonoids, alkaloids, terpenoids, and phenolic compounds, which function as natural reducing, stabilizing, and capping agents during nanoparticle formation. Compared to conventional chemical and physical methods, this green synthesis approach offers advantages including cost-effectiveness, simplicity, and the avoidance of toxic reagents. The review critically examines key factors influencing nanoparticle synthesis, such as pH, temperature, reaction time, and extract concentration, which play a significant role in determining particle size, morphology, and yield. Various characterization techniques reported in the literature are discussed, including UV-Visible spectroscopy for optical properties, X-ray diffraction (XRD) for crystalline structure, Fourier transform infrared spectroscopy (FTIR) for functional group analysis, and scanning and transmission electron microscopy (SEM and TEM) for morphological evaluation. Furthermore, neem-mediated ZnO nanoparticles demonstrate significant potential in diverse biological and industrial applications, including antimicrobial activity, antioxidant properties, and catalytic performance. Overall, this review highlights the effectiveness of plant-mediated synthesis as a sustainable alternative and underscores its importance in advancing green nanotechnology.

Keywords: *Bryophyllum pinnatum*, Bioactive compounds, Phytochemical analysis, Qualitative & quantitative analysis, UV-Visible spectroscopy, Medicinal plants.

Introduction

Nanotechnology has emerged as one of the most rapidly advancing fields in modern science, with metal oxide nanoparticles gaining significant attention due to their unique physicochemical and biological properties. Among these, zinc oxide (ZnO) nanoparticles are particularly important because of their wide band gap, high exciton binding energy, excellent stability, and diverse applications in areas such as electronics, optics, catalysis, environmental remediation, and biomedicine. However, conventional methods used for the synthesis of ZnO nanoparticles often involve toxic chemicals, high energy consumption, and expensive procedures, which raise environmental and safety concerns. In response to these limitations, green synthesis approaches have gained considerable interest as sustainable alternatives. Plant-mediated synthesis, in particular, has become a preferred method due to its simplicity, cost-effectiveness, and eco-friendly nature. Plant extracts contain a variety of bioactive compounds, including alkaloids, flavonoids, phenolics, terpenoids, and proteins, which act as natural reducing, capping, and stabilizing agents in nanoparticle formation. Among various medicinal plants, *Azadirachta indica* (neem) has been widely explored for nanoparticle synthesis due to its rich phytochemical profile and well-known medicinal properties. Neem leaf extract facilitates the rapid and stable formation of ZnO nanoparticles while enhancing their biological activity. The use of this plant not only reduces the dependence on hazardous chemicals but also improves the biocompatibility of the synthesized nanoparticles. This comprehensive review focuses on the green synthesis of ZnO nanoparticles using *Azadirachta indica* leaf extract, along with their characterization techniques and properties. It also highlights the mechanism of nanoparticle formation and discusses their potential applications in various fields. The study emphasizes the importance of sustainable nanotechnology and the growing role of plant-based synthesis in advancing environmentally responsible research and industrial applications.

Literature Review

Green synthesis of zinc oxide (ZnO) nanoparticles using *Azadirachta indica* (neem) leaf extract has emerged as an eco-friendly alternative to conventional physical and chemical methods. Traditional synthesis routes often involve toxic chemicals and high energy consumption, whereas plant-mediated methods are cost-effective, sustainable, and biocompatible. Neem leaves are rich in phytochemicals such as flavonoids, terpenoids, glycosides, and phenolic compounds. These biomolecules act as **reducing and stabilizing (capping) agents**, converting zinc salts into ZnO nanoparticles and controlling their growth and morphology. During synthesis, the addition of neem extract influences nucleation and particle size, often producing stable, well-dispersed nanoparticles with enhanced functional properties.

Characterization of biosynthesized ZnO nanoparticles is typically performed using techniques such as:

UV-Visible spectroscopy (confirms nanoparticle formation via absorption peaks)

X-ray diffraction (XRD) (reveals crystalline structure, usually hexagonal wurtzite phase)

Fourier transform infrared spectroscopy (FTIR) (identifies functional groups involved in reduction/capping)

Scanning/Transmission electron microscopy (SEM/TEM) (determines morphology and size)

Studies report that neem-mediated ZnO nanoparticles are generally nanosized, crystalline, and often spherical or polycrystalline in structure. They exhibit significant **antimicrobial, photocatalytic, and biomedical activities**, often outperforming chemically synthesized counterparts due to surface functionalization by plant biomolecules.

In conclusion, green synthesis using *Azadirachta indica* leaf extract is a promising, environmentally benign approach for producing ZnO nanoparticles with desirable physicochemical and biological properties. This method supports sustainable nanotechnology and has wide applications in medicine, environmental remediation, and material science.

Research Methodology

This review adopts a systematic and structured approach to analyze existing literature on the green synthesis and characterization of zinc oxide nanoparticles (ZnO NPs) using *Azadirachta indica* leaf extract. The methodology is designed to ensure comprehensive coverage, reliability, and critical evaluation of published research in this domain.

1. Research Design

The study is based on a qualitative review methodology, focusing on secondary data collected from previously published research articles, review papers, and scientific reports. The aim is to synthesize current knowledge regarding synthesis techniques, characterization methods, and applications of neem-mediated ZnO nanoparticles.

2. Data Sources and Search Strategy

Relevant literature was collected from reputable scientific databases and publishers, including Google Scholar, ScienceDirect, SpringerLink, PubMed, and IEEE Xplore. A systematic search strategy was employed using combinations of keywords such as:

“Green synthesis of ZnO nanoparticles”

“*Azadirachta indica* mediated nanoparticles”

“Neem leaf extract ZnO synthesis”

“Characterization of ZnO nanoparticles”

“Plant-based nanoparticle synthesis”

Boolean operators (AND, OR) were used to refine search results and ensure inclusion of highly relevant studies. Only peer-reviewed articles published in English were considered.

3. Inclusion and Exclusion Criteria

To maintain the quality and relevance of the review, specific criteria were applied:

Inclusion Criteria:

Studies focusing on green synthesis of ZnO nanoparticles using plant extracts, particularly *Azadirachta indica*

Research articles reporting synthesis procedures and characterization techniques (e.g., XRD, FTIR, SEM, TEM, UV-Vis)

Papers discussing biological or environmental applications of ZnO nanoparticles

Publications from the last 10–15 years, along with a few foundational studies

Exclusion Criteria:

Studies involving chemical or physical synthesis without biological components

Articles lacking sufficient experimental or methodological details

Non-peer-reviewed sources, abstracts, or unpublished data

Duplicate studies or irrelevant topics

4. Data Extraction and Organization

Selected studies were carefully reviewed, and relevant information was extracted, including:

Type of zinc precursor used (e.g., zinc nitrate, zinc acetate)

Preparation method of *Azadirachta indica* leaf extract

Reaction conditions (temperature, pH, time)

Size, shape, and morphology of synthesized nanoparticles

Characterization techniques and findings

Reported applications and performance outcomes

The extracted data were systematically organized into thematic categories such as synthesis methods, characterization techniques, and applications.

5. Analysis and Synthesis of Data

A comparative and descriptive analysis approach was used to evaluate the collected data. Studies were compared based on synthesis parameters, nanoparticle properties, and performance outcomes. Emphasis was placed on identifying:

Common trends and patterns in synthesis and characterization

The role of phytochemicals in nanoparticle formation

Advantages of green synthesis over conventional methods

Variations in results due to methodological differences

6. Characterization Techniques Considered

The review specifically examines commonly used characterization techniques, including:

X-ray Diffraction (XRD) for crystal structure

Fourier Transform Infrared Spectroscopy (FTIR) for functional group analysis

Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) for morphology

UV–Visible Spectroscopy for optical properties

Energy Dispersive X-ray Analysis (EDX) for elemental composition

These techniques were analyzed to understand how they contribute to confirming nanoparticle formation and properties.

7. Limitations of the Methodology

Certain limitations were acknowledged in this review:

Dependence on available published data, which may introduce publication bias

Variability in experimental conditions across studies, affecting comparability

Limited access to some subscription-based journals

Potential inconsistencies in reporting nanoparticle characteristics

8. Ethical Considerations

All sources of information were properly acknowledged to avoid plagiarism. The review strictly relies on publicly available data and does not involve any experimental work on human or animal subjects.

Expected outcomes

Establish *Azadirachta indica* leaf extract as an effective, eco-friendly reducing and stabilizing agent for ZnO nanoparticle synthesis.

Identify optimal synthesis parameters influencing particle size, morphology, and stability.

Confirm structural, morphological, and optical properties using standard characterization techniques (XRD, FTIR, SEM/TEM, UV–Vis).

Demonstrate enhanced antimicrobial, antioxidant, and photocatalytic activities of the synthesized ZnO nanoparticles.

Highlight advantages of green synthesis over conventional methods in terms of cost, safety, and sustainability.

Identify research gaps such as lack of standardization, scalability challenges, and need for toxicity studies.

Conclusion

In conclusion, the green synthesis of ZnO nanoparticles using *Azadirachta indica* (neem) leaf extract represents a promising, sustainable, and environmentally benign approach compared to conventional chemical and physical methods. The rich phytochemical composition of neem leaves, including flavonoids, terpenoids, phenolics, and other bioactive compounds, plays a crucial role in acting as reducing, capping, and stabilizing agents during nanoparticle formation. This leads to the controlled synthesis of ZnO nanoparticles with desirable morphology, enhanced stability, and improved physicochemical properties. Various characterization techniques such as UV–Visible spectroscopy, X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), and transmission electron microscopy (TEM) confirm the successful formation of crystalline ZnO nanoparticles with nanoscale dimensions and distinct surface functionalities. The green route not only eliminates the use of hazardous chemicals but also makes the process cost-effective and suitable for large-scale production. Furthermore, ZnO nanoparticles synthesized through this method exhibit significant potential in diverse applications, particularly in antimicrobial, anticancer, antioxidant, environmental remediation, and sensing fields. Overall, this review highlights that *Azadirachta indica*-mediated green synthesis of ZnO nanoparticles is a highly efficient and sustainable strategy that aligns with green chemistry principles and offers broad prospects for future scientific and industrial applications.

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Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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